Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Enhancement of Electrical Properties by Tailoring Nanoparticles in Holmium-doped YBa2Cu3O7-d Superconductors**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**3**	

Enhancement of Electrical Properties by Tailoring Nanoparticles in Holmium-doped $YBa_2Cu_3O_{7-\delta}$ Superconductors

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Background: High-temperature superconducting (HTS) tape and wire are promising for high power density shipboard motor and generator applications. There is a need, however, for improving the performance and stability of these materials in high magnetic fields in order to fully exploit this technology. The Naval Research Laboratory, with our extensive expertise and sophisticated capabilities for microstructural analysis, has been approached by and is working closely with several HTS wire processing groups, including HTS manufacturers American Superconductor Corporation and Metal Oxide Technologies Incorporated, as well as the U.S. Air Force Research Laboratory, to understand the basic relationships between microstructure and performance of HTS tapes.

Flux Pinning in Superconductors: Magnetic flux penetrates a Type II superconductor in the form of "vortices," which consist of circulating currents surrounding the flux. If these vortices move, an effective resistance is created, which degrades the critical current density and the transition temperature of the superconductor. If the vortices are prevented from moving, by "pinning" them, this enhances the critical current. This mechanism is suggested in Fig. 4, which depicts a slab of superconductor under the actions of a current and a magnetic field. The presence of flux pinning centers, such as second phase particles, for example, results in a pinning force that inhibits vortex motion. Pinning centers are most effective when the size and spacing is comparable to that of the vortices, on the order of 10 to 100 nm; hence, dense dispersions of nanoparticles in that size range provide very effective flux pinning.

Nanoparticles in YBCO: Figure 5(a) shows a transmission electron microscopy (TEM) image of a distribution of nanoparticles in the size range of 10 to 100 nm in an HTS coating of composition $YBa_2Cu_3O_7$ (YBCO) doped with holmium (Ho:Y ratio 1:1). This particular specimen was submitted to NRL for analysis by American Superconductor Corporation. The HTS coating is formed by high-rate metal-organic deposition and subsequent heat treatment. NRL determined that two types of nanoparticles, $(Y_xHo_{1-x})_2O_3$ and Cu-Ba-Ho-Y (exact stoichiometry yet to be determined), are formed during the deposition process. Figure 5(b) shows one partially faceted $(Y_xHo_{1-x})_2O_3$ particle, and Fig. 5(c) is a high-resolution TEM image of the interface between the matrix and a nanoparticle, showing that it is crystallographically not fully coherent. Figure 5(d) shows a TEM image of several nanoparticles in another Ho-doped YBCO specimen. The dark lobes around the particles are due to strain fields. The results indicate that the nanoparticles are associated with relatively large strain fields, and it is these strain fields that likely provide the pinning force for the vortices. NRL also has found that nanoparticles formed in YBCO films also can stabilize other defects such as twin boundaries, antiphase boundaries, stacking faults, intergrowth, and plane buckling, all of which result in additional contributions to vortex pinning.[1]

Crystallographic Twins: Crystallographic twin boundaries, i.e., grain boundaries of relatively good atomic fit between regions of different (but symmetrical) crystallographic orientation, provide extra pinning, although they are less effective than nanoparticles. It is known that (110) twins (twins whose boundaries lie parallel to a (110) direction in the crystals) form during transformation from the tetragonal to the orthorhombic phase, as the material is cooled from high processing temperatures. Figure 6(a) shows a Ho-doped YBCO specimen with a large number of (110) transformation twins (the linear features), in addition to a high density of nanoparticles. By correlating the density and sizes of the nanoparticles and the twins with the critical current density of the HTS specimens, and studying these features as a function of excess holmium content, the optimum composition for tailoring critical current retention in magnetic fields is found. NRL also has identified an interesting interaction between nanoparticles and twin boundaries. Figure 6(b) provides a high-resolution TEM image of twin boundaries that appear to be bent in the vicinity of a nanoparticle, presumably due to the presence of the strain field around the nanoparticle. Investigation of this observation is continuing.

Significance: Basic understanding of the effects of different kinds of flux-pinning features in superconducting coatings, such as nanoparticles and twins, allows the tailoring of the superconductor performance of HTS wire in magnetic fields. In particular, in superconducting motor and generator coils, there are substantial magnetic fields perpendicular to the superconducting tape, which produce a very large suppression of the critical current in the YBCO. With the controlled addition of flux-pinning nanoparticles, twin boundaries, and other defects through holmium doping of YBCO, the critical current under perpendicular fields is substantially improved, reducing the amount of super-

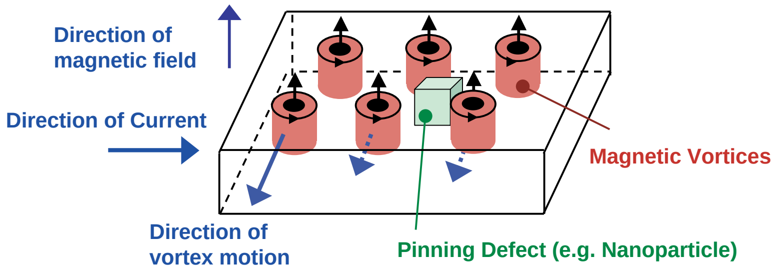

FIGURE 4
A schematic diagram illustrating the concept of pinning of the vortices by nanoparticles embedded in the superconductor.

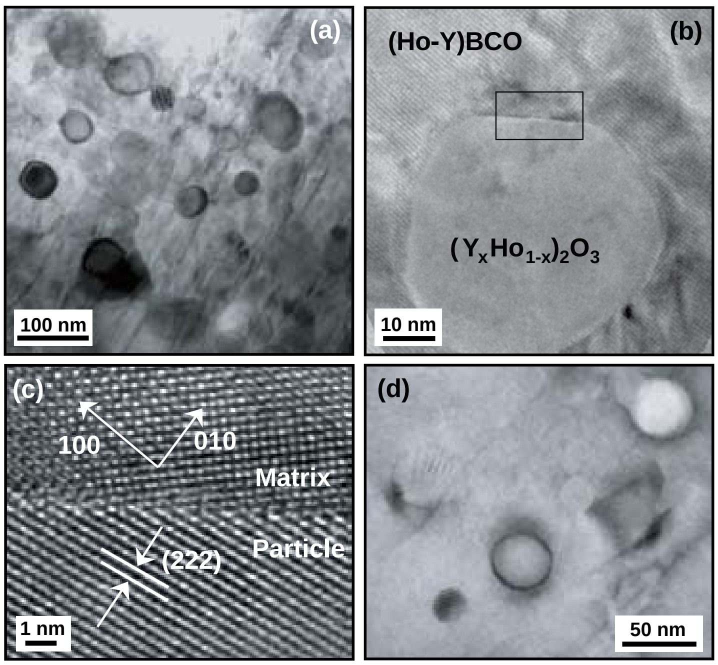

FIGURE 5
(a) A bright-field transmission electron microscopy (TEM) image showing the nanoparticles in the superconducting matrix in a Ho-doped YBCO sample. (b) A high-resolution TEM (HRTEM) image showing a coarse $(Y_xHo_{1-x})_2O_3$ particle. (c) A higher magnification HRTEM image showing that the particle/matrix interface of the coarse particle, obtained from the rectangular box in (b), is not fully coherent. (d) A fine particle showing the dark lobes around the particle suggesting that the particle is associated with a strain field.

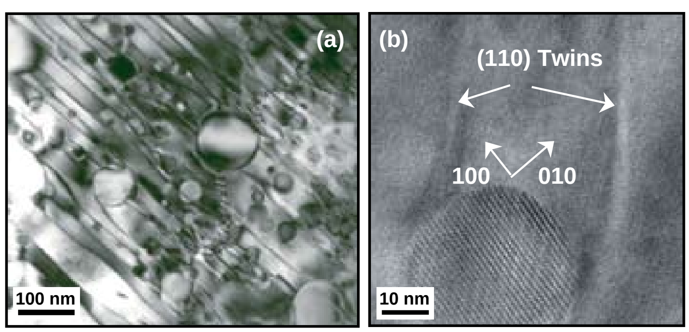

FIGURE 6
(a) A bright-field TEM image near the [001] zone of the superconducting matrix showing nanoparticles embedded in the matrix for a Ho-doped YBCO sample (lower Ho concentration than specimen of Fig. 5). Note the (110) twins. (b) HRTEM image showing the (110) twins. Note the apparent bending of twins close to the particle. Such bending could result from the interaction of strain fields present close to the particle and the twins.

conducting wire needed, and thus reducing both the size and the cost of the devices.

[Sponsored by NRL and ONR]

Reference

[1] R. Goswami, R.L. Holtz, M.W. Rupich, W. Zhang, and G. Spanos, "Effect of Holmium Additions on Microstructures in $YBa_2Cu_3O_{7-\delta}$," *Acta Materialia* **55**, 6746-6753 (2007) and references therein.

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